Partially Pyritised Holocene *Banksia* Cones from Tianjara Plateau, New South Wales

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Partially mineralised *Banksia ericifolia* L.f. cones collected from the Tianjara Plateau, New South Wales are described. The fossils have an outer layer of pyrite covering a charcoal interior. The cones were burnt prior to burial. Adsorbed organic material was subsequently oxidised under anaerobic conditions. Pyrite was formed by the precipitation of sulphide, produced by the concomitant reduction of sulphate, and ferrous ions. Carbon dating of material from the inside of one sample gave a conventional radiocarbon age of 6130 ± 80 BP.

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INTRODUCTION

Very few fossil *Banksia* cones have been reported (George, 1981). Perhaps the most famous are the Eocene fossil *Banksia archeocarpa* McNamara and Scott from the Kennedy Ranges of Western Australia (McNamara and Scott, 1983). Fossil cones from the Tertiary have been reported from brown coal deposits and gold-bearing sediments in the Latrobe Valley (Cookson and Duigan, 1950; Pike, 1953). Extinct *Banksia kingii* Jordan and Hill, which has recently been described from south-western Tasmania, flourished in the late Peistocene (Jordan and Hill, 1991).

This paucity of fossil *Banksia* cones is surprising, since abundant and varied fossils of *Banksia* leaves, or its very close relatives, are known from Tertiary and Quaternary sediments (Hill and Christophel, 1988; Jordan and Hill, 1991). *Banksia* cones are very robust and woody, and are therefore resistant to degradation, making them good candidates for preservation. The lack of fossil cones, compared to *Banksia* leaves, is likely to be the result of differences between the modes of fossilisation. The known fossil *Banksia* cones have mostly been found in sediments which did not contain leaves: for example, no leaves were found with *B. archeocarpa* (McNamara and Scott, 1983), there is no record of leaves from the gold bearing sediments from Victoria (Cookson and Duigan, 1950), and the leaves and cones of *B. kingii* occur in different sedimentary lenses at Melaleuca Inlet (Jordan and Hill, 1991). Only the cones from the Yallourn coal seams have been associated with leaves (Cookson and Duigan, 1950; Pike, 1953).

The most intensively studied Tertiary and Quaternary macrofossil deposits in Australia are water-transported leaf floras containing few large organic objects. Most *Banksia* cones are considerably more massive than any leaves, and are therefore likely to be deposited in different localities to the leaves, and, therefore, in sediments which are unlikely to be studied by palaeobotanists. Indeed, their massive size means that they are likely to be deposited in high-energy sediments, which are generally coarse and much less likely to produce the anaerobic conditions normally required for preservation and subsequent mineralisation. The cones of *B. kingii* were found in much coarser sediments than the leaves, which occurred with leaves and small fruits of other species (Jordan and Hill, 1991; Jordan *et al.*, 1991).

The process of substitution of the organic material of prospective fossils by inorganic material may allow conditions which are favourable for the preservation of massive woody structures (e.g. the occurrence of petrified wood). Indeed, the cones of *B. archeocarpa* from Western Australia are mineralised. This paper describes the process of pyritisation of *B. ericifolia* L.f. cones from south-eastern New South Wales, which has resulted in apparently durable replicas of the organic cones. This process has occurred under depositional conditions unlike those of most other plant fossils.

Site Description

Tianjara Plateau, which is part of Morton National Park, is near the southern extremity of the extensive Sydney Basin region (Fig. 1). The surface of the plateau, which is a flat-topped erosional remnant, is formed of the Nowra Sandstone of the Shoalhaven Group (Herbert and Helby, 1980). It owes its existence to the presence of the flat-lying cliff-forming Permian sandstone and marine quartzose sandstone, which overlies softer Permian mudstones. Erosion of the plateau appears to be mainly by cliff retreat rather than lowering of the plateau surface. It is possible that the surface of the plateau has remained virtually unchanged for hundreds of thousands or even millions of years.

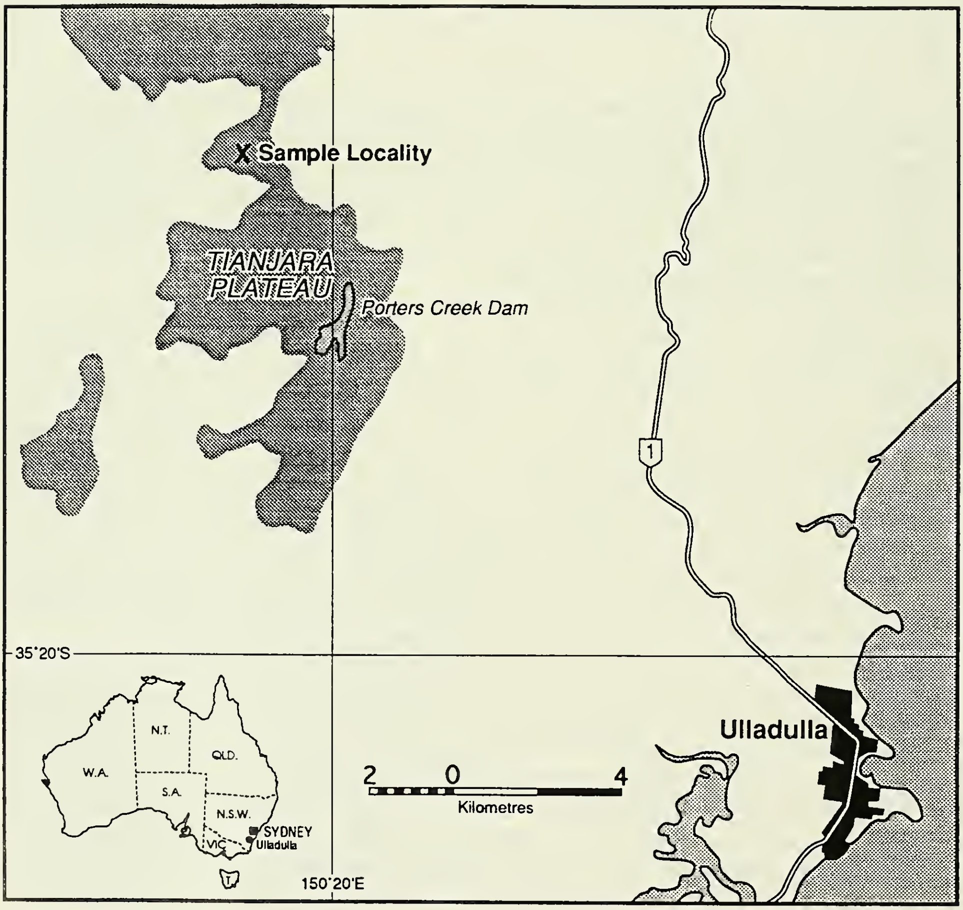

Fig. 1. Map of the region from which the samples were collected.

The soils, derived from the underlying sandstone rock, are nutrient-poor. Some downslope soil movement may be possible by creep, slumping, and the action of wind and water. Many areas are (semi-) permanently waterlogged and perched swamps are present. Ulladulla, a coastal town approximately 20 km to the southeast receives an annual rainfall of 1266 mm, with monthly average temperatures ranging from 12°C in winter to 21°C in summer. It is likely that the plateau receives more rain, and that the temperature range is more extreme.

The fossil samples were collected from the bed of an abandoned fire trail. The trail sloped gently from the north-west; approximately 200 m to the north-west of the collection site, the trail climbed a small 5-10 m high scarp. Above this minor cliff line the terrain was flat, with very little soil and large areas of open rock. A similar situation occurred downhill from the sample site at the bottom of the slope. However, sandy soil derived mainly from the upslope area had accumulated to form the slope from the scarp to the next essentially level area. It appeared that the soil was deposited after being washed from higher areas or from erosional processes at the cliff line. Patches of the soil were reddish in colour, suggesting the presence of iron. The cleared fire trail provided a watercourse for run-off from the higher area, as the lack of thick plant cover reduced the resistance to water flow that would occur elsewhere.

The fossils lay in patches across the fire trail and were partially embedded in a matrix of unconsolidated sandy soil. The long axis of the samples were generally horizontal to the soil surface. Excavation to a depth of 30-40 cm revealed no further samples, even though the cones were abundant at the surface. The number of fossils evident at the surface varied considerably over a period of 2 years.

The flora in the vicinity of the collection site consisted of thick heath vegetation, and included shrubs of the genera *Banksia*, *Acacia*, *Hakea*, *Boronia*, *Leptospermum*, *Epacris* and others. Occasional patches of *Eucalyptus* were also present, especially where deeper soil had accumulated near small cliff lines. Such flora is typical of some of the Sydney Sandstones. Three *Banksia* species occurred in the immediate area of the sampling site: *B. ericifolia* var. *ericifolia* L.F., *B. spinulosa* var. *spinulosa* Smith and *B. paludosa* R.Br. *B. serrata* L.F. also occurred within 1 km of the site. The *Banksia* taxonomy followed in this paper is that of George (1981).

Description of Fossil Material

Samples of the fossil *Banksia* cones (woody infructescences) were collected during July, 1991. The fossil cones were up to 8 cm in length and 3 cm in diameter (Figs 2a and 2c). Complete cones were relatively scarce, but smaller fragments consisting of partial cones were common. The fossils typically consisted of three distinct layers. The interior of the fossils was charcoal, though in at least one case, original woody material remained. Surrounding the charcoal was a layer, 1 to 10 mm thick, of a mineral identified by chemical tests to be pyrite (FeS_2) (I. R. Willett, personal communication). On the outside was a thin layer of yellow-orange material, which was probably jarosite, $[KFe_3(OH)_6(SO_4)_2 5H_2O]$, a common oxidation product of pyrite. The broken surfaces of the partial cones showed the same structure, indicating that the mineralisation process began after the cone was broken and also after the plant material had been burnt.

The external and internal structures of the fossils were generally well preserved (Figs 2a and 2c). In particular, the floral bracts were evident in both whole cones and in cross section. However, the follicles appeared to have been worn back to the surface formed by the floral bracts. Some modern, charred, but non-mineralised cones of *B. ericifolia* collected from the surface nearby (Figs 2b and 2d) had the same characteristics.

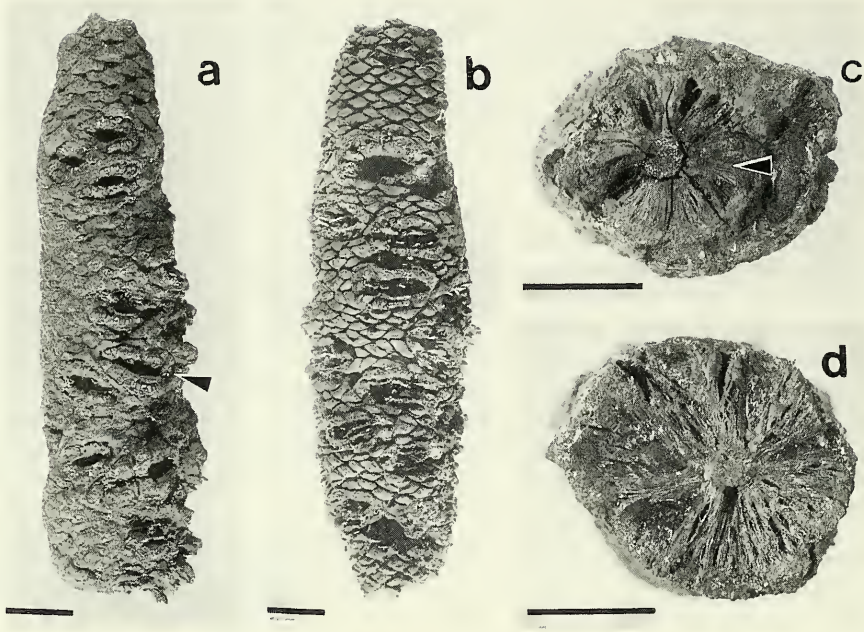

Fig. 2. Photographs of (a) partially pyritised *Banksia ericifolia* cone. The arrow points to the base of a woody follicle. The floral bracts are the regularly distributed more or less diamond shaped structures. (b) Burnt cone of extant *B. ericifolia* collected from the ground in the same area. (c) Transverse section of a partially pyritised cone. The darker area on the right hand side of the inside of the cone indicated by the arrow was soft, black and charcoal-like. (d) Transverse section of a burnt cone of extant *B. ericifolia* from the same area. Scale bars in all figures are 1 cm.

The fossil cones (Figs 2a and 2c) could not be distinguished morphologically from these charred but non-mineralised *B. ericifolia* cones. They were similar in the following aspects: overall size; size and shape of the follicle bases; size and shape of the bracts; and the size and distribution of the bracts and cone axis in cross section. Apparent differences between the fossil and extant cones in diameter, and the shape of the bracts, can be attributed to the greater erosion of the fossil cones and within-population variation.

The fossil cones differ morphologically from all other eastern Australian species. The follicle bases of the cones are nearly as broad as they are long (Fig. 2a), whereas those of *B. spinulosa* are smaller and more elongate. *Banksia ericifolia* and *B. spinulosa* are the only eastern Australian members of *Banksia* series *Oncostylis. Banksia serrata*, *B. aemula* R.Br. and *B. ornata* F. Muell. ex Meissner (series *Orthostylis*) all have much more massive follicle bases. The species of *Banksia* section *Salicinae*, which includes *B. marginata* Cav., *B. integrifolia* L.F., *B. paludosa*, *B. oblongifolia* Cav. and several other species, all have follicle bases which are much longer than broad. Therefore it was concluded that the fossils belonged to the species *B. ericifolia*.

The age of one of the fossil samples was determined by radiocarbon dating. The sample was cleaned carefully prior to analysis, and treated with acid (to remove soluble iron) and alkali, which removes adsorbed humic and other organic substances from within the matrix of charcoal samples. It was found that a large amount of such material was leached from the sample (G. Taylor, personal communication). The age of the sample was determined to be 6130 ± 80 BP (S.U.A. 3024). This age might be a slight underestimate due to possible contamination by organic-rich water of younger radio-arbon age (Colhoun, 1986).

Discussion

Pyritised plant macro-fossils are relatively common (Kenrick and Edwards, 1988). Tertiary ironstones which contain well-preserved leaf floras are widespread in Tasmania and are well known in Western Australia (R. S. Hill, personal communication). These fossil floras are poorly recorded in palaeontological literature, probably because of the difficulties in dating them and because the destruction of the organic cuticle makes identification of the fossil leaves very difficult. The fossils discussed in this paper, however, are novel in that large fruiting bodies have been preserved and that only an outer skin has been pyritised, while the interior of the fossils consists of charcoal or, in rare examples, woody material.

The similarity of the fossil material and modern charred, but non-mineralised, *B. ericifolia* cones indicates that the fossil cones were burnt prior to burial and mineralisation. *B. ericifolia* var. *ericifolia* regenerates after fire from seed (George, 1981). Thus, the fruiting cones have to be able to survive the high temperatures experienced during fires. The seeds are released from the cones after the fire, but the cones remain attached to the burnt plant.

It is probable that the fossils and the similar modern burnt cones had undergone two burning processes. Tianjara Plateau was burnt extensively during large bushfires in early November, 1988, and many dead *B. ericifolia* var. *ericifolia* were present on the plateau when the fossils were collected. These plants still had the cones attached to the stems; the exerted woody follicles had opened, but were not burnt back to the floral bracts. Inspection of the cones showed that they still possessed a considerable amount of organic material. On the ground in the same area were many charred cones that had been converted entirely to charcoal (Figs 2b and 2d). We suggest that these cones had been burnt a second time; the fire-resistant nature of the cones was such that, rather than total combustion, charring to charcoal occurred. The second fire had also caused the cones to fall from the dead plants. The follicles on the outside of the cone, however, were burnt back to the surface formed by the floral bracts during this second burning.

Preservation of plant parts will only result if biological and mechanical breakdown is avoided. Rapid entry into anaerobic conditions is generally thought to be necessary for the preservation of unburnt organic matter (Ferguson, 1985). If exposed to oxygen, bacterial respiration of the organic material will occur. Under anaerobic conditions, this respiration is either halted, or, in the presence of sulphate-reducing bacteria and sulphate ions, continued with the concomitant formation of sulphide ions. If iron is also present, pyrite (FeS_s) is eventually precipitated. Relatively high concentrations of sulphate would be expected at near coastal sites such as the Tianjara Plateau due to the transport of sulphate-containing aerosol particles, formed by breaking waves, from the ocean. Although the soil at the collection site did not appear particularly ferruginous, patches of soil nearby were brick red in colour and probably contained relatively high concentrations of iron. Thus the reduction of organic material and the formation of pyrite would be expected under anaerobic conditions in the perched swamp areas near where the fossils were found.

Charcoal, however, is not degraded by either anaerobic or aerobic bacteria. The question then is: what organic material was oxidised during the formation of the pyrite present in the fossils? It is possible that organic material remained after charring, but more probable that a secondary source of carbon occurred. Many of the modern charcoal cones at the surface were covered by mosses and other plants; this plant material could have provided the organic carbon required. No evidence, however, of fossilised mosses on the outside of the cones was observed. However, charcoal strongly adsorbs organic chemicals; organic matter excreted by the mosses or carried in water which washed over the cones could have sorbed to the charcoal before they entered anaerobic conditions. Evidence for this mechanism was provided by the fact that a large amount of organic material was leached from the samples on treatment with alkali. This observation also suggests that the process of pyritisation would probably have continued if the sample remained in the requisite chemical environment. Such a process would also explain why only an outer shell was pyritised, as dissolved organic species would be concentrated in the adsorption process near the surface of the charcoal. However, it is possible that the pyrite layer formed a seal over the surface of the cones precluding the further entry of bacteria and/or sulphate ions.

Compared to the fossils, the modern charred cones were very fragile. It is therefore unlikely that the burnt cones were transported any distance before they were buried, even though they could have remained at the surface for a considerable length of time. They were possibly buried by slumping or a similar erosional process; the fragility of the cones and the flatness of the plateau appear to preclude deposition in stream sediments. However, the fossilised cones were considerably more robust, and could have been transported by water to the site from which they were collected. As mentioned above, the sampling site was an old fire trail, which would provide a pathway for water to flow from close-by higher land during the frequent heavy rainstorms that occur in the area. Excavations at the site of collection revealed no fossils deeper than a few centimetres — most of the fossils were only partly embedded in the sandy matrix. It is probable that the fossils had been transported by water flow from a higher point and deposited on the flatter slope. Searches for *in situ* fossils failed.

The processes suggested for the partial mineralization of the *Banksia* cones provide a novel mechanism for the formation of fossils. Pyritization is generally thought to proceed via direct precipitation of iron sulphides as organic matertial is oxidized (Kenrick and Edwards, 1988), resulting in little original material remaining. In this case, after conversion of the bulk of the organic carbon to charcoal, only a thin surface layer of pyrite is formed. The process makes the material more robust, and also allows the charcoal to be preserved within the fossil.

The age of the fossil provides evidence for the existence of *B. ericifolia*, and by inference, a fire adapted flora, at this locality during the early Holocene. The presence of *B. ericifolia* is not surprising considering the current nutrient-poor status of the local soils and the geological stability of the environment. It is interesting to note that the samples were collected from near the southern extremity of the current range of this species (Taylor and Hopper, 1988), indicating that it has probably been present over this range for at least the last 6000 years. The existence of a fire-adapted flora at this locality is also not surprising, considering the long history of high fire frequencies in south-eastern New South Wales (Singh *et al.*, 1981).

The occurrence of sub-fossil *Banksia* cones on Tianjara Plateau suggests that similar material could be found throughout the swampy highland plateaux that are prevalent along the south coast of New South Wales. The samples also suggest processes that could lead to more complete fossilisation: the charring and partial pyritisation of the cones results in a more chemically, mechanically and/or biologically stable form that could be further lithified after burial.

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